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Influence of laser radiation polarisation on small-scale self-focusing in isotropic crystals

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Abstract. **The gain of spatial noise in the field of an intense linearly polarised wave, propagating in a BaF_2 cubic crystal with orientation [001], is directly measured. The previously predicted strong dependence of the evolution of small-scale self-focusing on the angle between the radiation polarisation vector and the crystallographic axis of crystal is demonstrated.**

Keywords: *small-scale self-focusing, cubic crystals, anisotropy of cubic nonlinearity, B-integral.*

1. 1. Introduction

Currently, isotropic (cubic) crystals are widely used in the design of high-power lasers. They serve as materials for active and magnetoactive elements; optical windows; elements for passive Q switching and passive mode locking; and generators of crossed polarised waves (XPWs), which are the basis of the method for increasing the time contrast of high-power ultrashort laser pulses. Generally, the thickness of optical elements, which ranges from several millimetres to several centimetres, limits the laser radiation intensity passing through them, because, in the case of highly intense beams, their small-scale self-focusing (SSSF) may occur as a result of amplification of spatial perturbations due to the cubic nonlinearity [1].

The theory of SSSF in glasses has been developed since the 1960s. Harmonic small-scale spatial perturbations of radiation are generally considered against the background of an intense plane wave. Bespalov and Talanov [1] found (within the linearised theory) the boundary of the domain of the perturbation instability and the maximum value of its increment. The next problem was to calculate the gain of the noise component as a function of its spatial frequency and its phase at the input of a nonlinear medium. This problem was solved in the case of an isotropic medium for linearly polarised radiation [2]. An exponentially growing solution was considered for an arbitrary polarisation within the linearised theory, and the boundary of the instability domain and the maximum increment were found [3, 4]. The maximum increment of instability is proportional to the B-integral: $B = k\gamma IL$, where I is the radiation intensity; k is the wave vector; L is the length of the medium; and γ is the nonlinearity coefficient, which is determined by the diagonal component of the fourth-rank nonlinear susceptibility tensor $\chi^{(3)}$. At large values of the B-integral ($B > 3$), SSSF leads to a strong modulation of the beam intensity and a damage of optical elements, as was evidenced by numerous experiments. The gain of spatial perturbations was directly measured for the first time in 2009 [5]. The experimental results with neodymium laser glass completely confirmed the theoretical predictions.

Nevertheless, SSSF in isotropic (cubic) crystals was investigated for the first time only in 2016 [6]. A cubic crystal is a medium having isotropic linear properties but anisotropic nonlinearity: the $\chi^{(3)}$ tensor contains additional components in comparison with that for glass. As a result, two new important parameters arise: the crystal orientation and the tilt angle of the radiation polarisation vector with respect to the crystallographic axis of the crystal (hereafter, we restrict ourselves to linearly polarised incident beams). The development of SSSF in cubic crystals with orientations [111], [001], and [101] was theoretically investigated in [6]. It was shown that the instability in the crystals with orientation [111] starts developing at lower intensities than in the crystals with orientations [001] and [101]. For the two latter orientations, the increment of instability depends strongly on the radiation polarisation; therefore, SSSF can be suppressed to a great extent by choosing the optimal polarisation.

In this work, we performed direct measurements of the gain of small-scale inhomogeneities (noise) in a BaF_2 crystal with the [001] orientation. The results confirmed the predictions of paper [6].

2. Schematic of the experiment

A schematic of the experiment is presented in Fig. 1. The front end [7, 8] of the PEARL laser complex [9] was used as a high-power light source. A beam 6 mm in diameter with a uniform intensity distribution was cut by a diaphragm from the output beam 20 mm in diameter. The laser pulse energy after passing through the diaphragm was 4 mJ, and the pulse width was 60–70 fs. To monitor the pulse duration and energy, some part of the radiation before the nonlinear crystal was coupled by 200-μm-thick glass plates to a single-pulse autocorrelator and pyroelectric sensor. According to the estimates, the aforementioned plates and air gap did not make any significant contributions to the B-integral, 'accumulated by' the radiation. Mirror (*1*) directed the beam to a 6-mm-thick nonlinear BaF_2 crystal (*3*) with the [001] orientation. Crystal (*3*) was fixed in a mechanical mount, which provided its rotation by 360° around the laser beam axis to study the influence of the angle between the radiation polarisation vector and the crystallographic axis of the crystal on the noise

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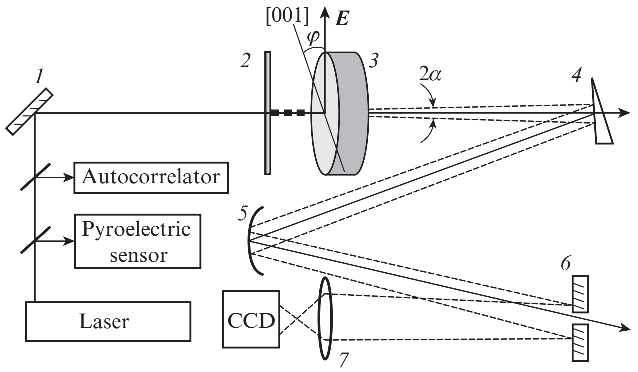

Figure 1. Schematic of the experiment:
(*1*) plane mirror; (*2*) matted plate; (*3*) BaF_2 crystal with orientation [001]; (*4*) wedge-shaped neutral density filter; (*5*) spherical mirror; (*6*) plane mirror with a hole; (*7*) lens.

gain. After passing through the nonlinear crystal, the radiation intensity was reduced by a factor of 25 [as a result of the reflection from the front face of wedge-shaped neutral density filter (*4*)] and reflected from spherical mirror (*5*) with a focal length of 280 mm. The reduction of the radiation intensity is necessary to exclude the optical air breakdown in the focus of the spherical mirror. To observe the spatial noise amplification (as in [5]), plane mirror (*6*) with a hole 1.5 mm in diameter was located in the focal plane of spherical mirror (*5*) to cut off the main (rather than noise) beam. The diameter of the hole was sufficiently large to make the main beam pass completely (including wings) through it. As a result, only the noise radiation was reflected from mirror (*6*), and its image which transferred by lens (*7*) to a CCD camera, which recorded the angular spectrum of spatial noise.

A thin (200 μm), slightly matted glass plate (*2*), located at a distance of $l = 17$ mm before the BaF_2 crystal, was used as a spatial noise source. This small length was chosen to prevent all spatial harmonics falling in the domain of strong instability from escaping from the beam aperture. At the same time, the distance from mirror (*1*) to plate (*2*) was, vice versa, sufficiently large to allow all spatial harmonics falling in the strong instability domain to leave the beam aperture. Due to this, the beam was self-cleaned before plate (*2*) [10, 11]. Thus, matted plate *2* was the only noise source. If we consider plate (*2*) as an ideal amplitude mask, all spatial noise harmonics have the same phase in the plate plane; this circumstance was taken into account in the numerical simulation (see below). The angular spectrum of nonamplified noise is shown in Fig. 2a. To measure it, we multiply elongated the laser pulse by changing significantly the distance between the compressor gratings, so as to make the nonlinearity in the BaF_2 crystal negligible.

3. Experimental results and discussion

According to the SSSF theory, the gain of spatial perturbations both in glass [2, 5, 12] and in an isotropic crystal [6] depends not only on the angle between the wave vector and the z axis of the system but also on the phase difference between the strong and perturbation waves at the input of the nonlinear medium. This phase difference, in turn, depends on the angle α in correspondence with the evident formula

$$\Delta\Psi = \pi\alpha^2 l/\lambda,$$

where λ is the wavelength. Here, we assume (see above) that this phase difference is zero for all α in the plane of matted plate (*2*). In our experimental geometry, this formula yields the gain spectrum modulation, i.e., the occurrence of rings in the amplified noise intensity distribution in the far-field zone, which we measured for the BaF_2 crystal (Fig. 2b) and Poteomkin et al. [5] observed for glass for the first time.

As was shown in [6], the noise gain in an isotropic crystal, in contrast to glass, depends on the angle φ between the electric field vector and crystallographic axis; for the [001] orientation, this dependence has a period of 90°. We measured the angular spectrum of the gain by dividing the intensity distribution in Fig. 2b by the intensity distribution in Fig. 2a and

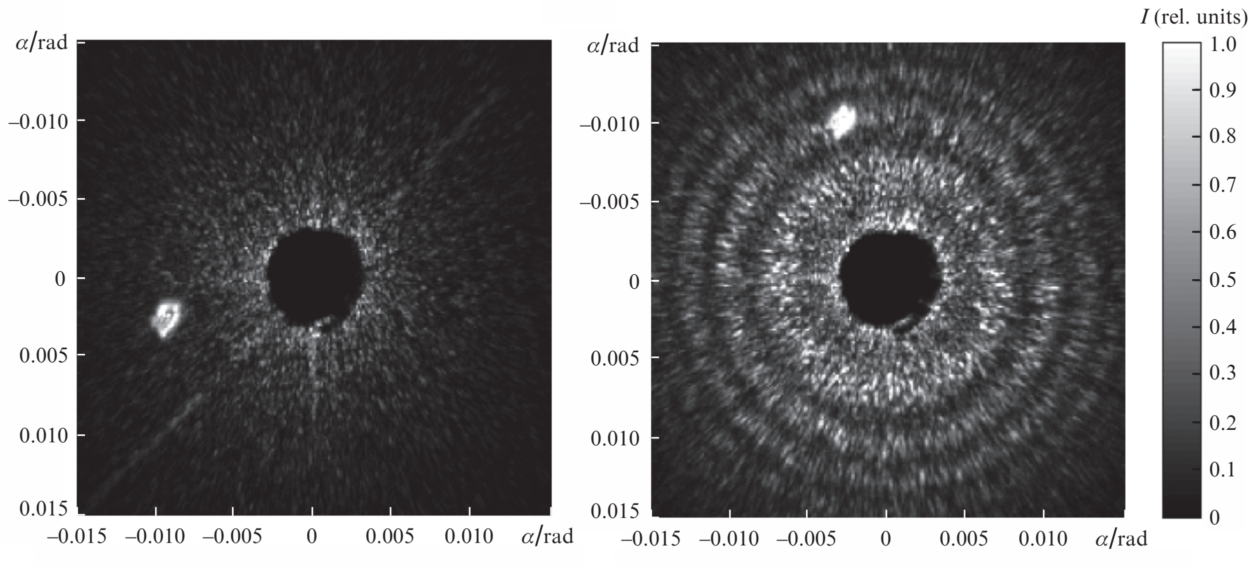

Figure 2. Angular spectra of (a) nonamplified and (b) amplified noise.

integrating over the polar angle. The gain spectra were measured for different φ values. Figure 3 shows the experimental and theoretical spectra. One can see that the experimental dependences are in qualitative agreement with the theoretical predictions. The smaller (as compared with predicted) modulation depth is explained by the insufficient resolution of the optics used to transfer the image to the CCD camera and by the deviation of the phase difference between the strong and perturbation waves in the plane of matted plate (*2*) from zero.

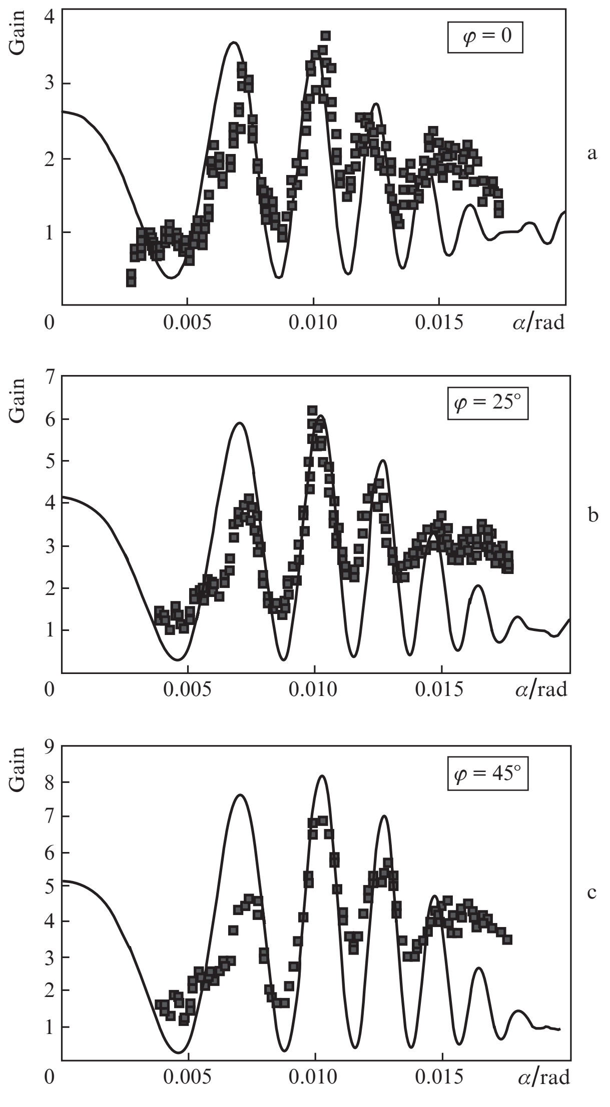

Figure 3. Angular spectra of the noise gain for three values of the angle between the vector of the electric field and the crystallographic axis of the crystal: (symbols) experimental data and (curves) theoretical predictions at $B = 0.9$.

Figure 4 shows the dependence of the integral (i.e., averaged over the spatial spectrum in the range of angles α = 0.005–0.016 rad) noise gain on angle φ. Several measurements were performed for each φ value. The large spread is explained by the fact that the pulse energy and duration and, therefore, the B-integral varied from shot to shot. Since the noise gain exponentially depends on the B-integral, even small fluctuations of the latter lead to large gain fluctuations. Figure 4 shows theoretical dependences for three values of the B-integral. Since the gain was found in the experiment by measuring an increase in energy rather than power (i.e., integrally for the entire pulse), the theoretical curves were also plotted by averaging over a Gaussian pulse, and the given values of the B-integral correspond to the pulse maximum. As can be seen in Fig. 4, almost all experimental points lie in the range of B = 0.75–0.9. The SSSF value is minimal at $\varphi = 0$, i.e., the crystallographic axes of the sample must be oriented parallel to the laser radiation polarisation vector. Note that, even at a relatively small value $B = 1$, the noise gains for the optimal $\varphi = 0$) and nonoptimal ($\varphi = 45°$) polarisations differ by a factor of 3.

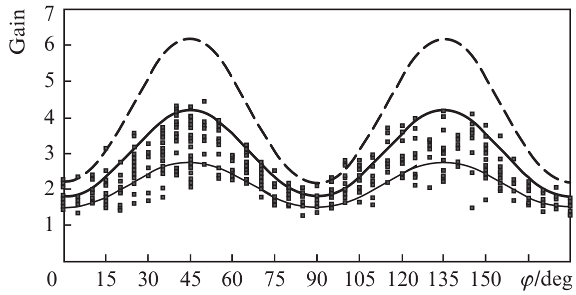

Figure 4. Dependences of the integral (averaged over the spatial spectrum) noise gain on angle φ: (symbols) experimental and (curves) theoretical results at B = (thin solid curve) 0.75, (bold solid curve) 0.9, and (dashed curve) 1.

4. Conclusions

The angular spectrum of the gain of small-scale perturbations in the field of an intense light wave propagating in an isotropic crystal with cubic nonlinearity was directly measured for the first time. The measurement results are in complete agreement with the predictions of the previously developed theory. In particular, the small-scale self-focusing was found to depend strongly on the noise wave phase at the crystal input and on the angle between the laser radiation polarisation vector and the crystallographic axis of the crystal. To minimise the small-scale self-focusing, it is necessary to orient the crystallographic axes parallel to the radiation polarisation vector.

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